

METHOD AND APPARATUS FOR ENHANCING
AN IMAGE USING DATA OPTIMIZATION
AND SEGMENTATION

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BACKGROUND OF THE INVENTION

The present invention relates generally to data image processing and, more specifically, to generating enhanced digital images utilizing image segmentation processes that involve depth buffer information in association with point selection projection images.

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The development of high resolution 3D (three-dimensional) imaging techniques, such as magnetic resonance imaging (MRI), computed tomography (CT), and rotation X-ray CT angiography (XRCTA), have led to situations where high volumes of image data are generated in the study of individual patients. In many cases, such as in 3D magnetic resonance angiography (MRA) and 3D CT angiography (CTA), the amount of detail per two-dimensional slice is small, but the high resolution detail of the full image volume is required in the diagnostic process. In one example, arterial beds are generally sparse, so there is typically a large amount of nonvascular image data present in a 3D angiographic image. As the resolution and volume coverage of MRA examinations have increased recently, having adequate means to effectively and efficiently review the available image information is a significant challenge for radiologists. Currently, there are three primary display techniques used for clinical evaluation of MRA data. The first technique is to display selected original cross-sectional MRA images. The second technique is to display oblique planar reformatted images. The last technique is to display a maximum intensity projection (MIP) image. The following discussion focuses mostly on MRA images; however, the discussion is equally applicable to other 3D angiography techniques such as CTA and XRCTA and to other volumetric visualization techniques in which selectable groups of image points are of interest.

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The original cross-sectional images, also referred to as slices, contain the maximum amount of information on a local level. Each image displays the transverse segments and cross sections of vessels that intersect the plane of the image. Sometimes, the vascular detail of interest may be observed in a single image. More often, because of the intricate paths of the vessels, many images must be viewed, and the information from each image must be integrated to formulate an understanding of the structure of interest. This method is inefficient since it requires a single slice to be displayed, which slice contains very little global information about any single intricate vessel in the overall vascular network.

The oblique planar reformatted images provide improved efficiency over the original images by displaying image planes that follow a segment of a vessel of interest through the three-dimensional image data. Each individual image still provides only local information and a complete view of the vascular bed is not obtained.

5 Volume rendering consists of the projection or rendering of an entire 3D image volume onto a single two-dimensional image. The volume is projected along parallel or diverging lines through the three-dimensional volume onto a two-dimensional image. The intensities along the projection line are transformed according to some specified transformation. Such rendering, in a variety of forms, has become very useful in assisting
10 the observer in the rapid and efficient interpretation of the large amounts of image data originally obtained. A simple form of volume rendering, which is also intuitive, is an X-ray-like summation of the image densities or intensities. Initial attempts at MRA found that when the summation type of volume rendering was used, the background signal was too large to the point of masking a majority of vascular details during the summation
15 process. The display capabilities were improved to the point where useful vascular details were observable when the rendering was performed by selecting only the maximum image value encountered along each projection line. This approach is known as the maximum intensity projection (MIP) algorithm and has been used in the development of a variety of MRA techniques. Other forms of volume rendering, such
20 as assigning opacities and translucencies to certain image values or regions of image values, have been applied and found useful. However, the MIP algorithm is dominant because of its simplicity and consistency in generating quality images.

The MIP algorithm is successful to the extent that the signal from vessels is greater than the signal of the surrounding tissues. In regions where vessels do not appear
25 overlapped, the MIP algorithm is sufficient to display vessels that are hyperintense relative to the variations in the overall background. Unfortunately, the MIP algorithm does not provide any information about vessels that are hidden below the intensity of other structures. Because of the sparseness of vessels, there is a significant amount of vessel detail that is not hidden and the MIP performs very well in increasing the amount
30 of vessel detail observed in a single image.

Although there is a loss of information in a MIP image, the MIP algorithm provides a large amount of useful information in a single display. The information density, or information content per image element, is much higher in a MIP image than in the original 3D source data. In other words, although the source image data contains
35 more total information, including some small arteries that would not appear in the MIP image, the density of vessel information in the source image data (i.e. the percentage of

image elements associated with vessels) is lower than in the MIP image. As discussed later, many investigators have tried to develop algorithms to overcome the limitations of the MIP algorithm, and, although these have been viewed as improvements, the improvements have not been sufficient for any of these algorithms to replace the MIP algorithm. The advantages of the MIP algorithm typically outweigh the disadvantages found therein. These advantages include reduced dynamic range, generally consistent image display, and improved signal difference to noise ratio (SDNR or contrast to noise ratio) for vessels that appear in the MIP. The artifacts in the MIP, although very real, are also well understood and can be "read through."

The MIP display contains a large amount of global information about the vascular system. The appearance of a MIP image is quite similar to that of an X-ray angiogram, but there are several differences. The MIP simply selects the image element with the maximum intensity along each projection line, while the X-ray projection is a summation of all densitometric information along each projection line. The MIP image is therefore a flat display having no depth information and no information about the thickness of the vessel through which the projection line passed, while in X-ray angiography the vessel brightness or darkness depends directly on the length of the X-ray projection path through the vessel. Thus, in regions where several vessels are overlapping in the MIP image, it is difficult to resolve specific vessel segments. Further, because the signal intensity is not related to the projection path length through the vessel, an increase in vessel signal is not observed for foreshortened vessels. There are other limitations that exist in the MIP algorithm. Statistical noise properties associated with the signal of the tissue background cause the signal level of the background in the MIP to increase with the projection volume thickness. Consequently, small vessels with signal levels that are slightly above the local background signal level may be lower than other background image elements along the projection line and, therefore, may not be observed in the MIP images. The limitations of the MIP can make it necessary to also review the original low information density cross-sectional images. When used in combination, the two display formats are a means for detecting and evaluating many types of vascular pathology. The review process, however, is rather time consuming, especially for complex cases.

Various attempts have been made to overcome the deficiencies that exist in the MIP algorithm. The appearance of small vessels in the MIP image can be improved by the use of zero filled interpolation (ZFI). The problem addressed by ZFI is that the arbitrary positions of the vessels relative to the reconstruction grid cause small vessels or vessel borders to be poorly rendered in the image due to the weighting of the voxel sensitivity function. ZFI reconstructs the image on a grid that is finer than the acquisition

grid, thereby reducing vessel jaggedness in the MIP image caused by partial volume effects and improving vessel continuity and visibility in the MIP image for subvoxel-sized vessels.

5 Other attempts to overcome the problems inherent in the MIP algorithm and to improve the two-dimensional rendering of MRA image data range from simple modifications of the MIP algorithm, to attempts at complete segmentation and redisplay of the vascular information contained in the original MRA data. These attempts include utilizing the traveling or sliding slab MIP technique; preprocessing the original MRA image data before application of the MIP algorithm; line-based segmentation, where the vessel voxels are segmented from the background image data, which is also similar to segmentation work performed in other fields; intensity based segmentation, where the vessel voxels are segmented based upon relative intensities and proximity in 3D; and interactive intensity based segmentation, where vessel voxels that cannot be segmented based upon intensity are displayed over a wider gray scale range than those that can be segmented.

15 MRA display capabilities are also useful in a number of intracranial applications. There are various disease processes for which the diagnosis can benefit from improved image display capabilities. These diagnostic capabilities include predicting the need for thrombolysis in stroke conditions, diagnosing vasculitis and other occlusive diseases, identifying intracranial tumors and arterial venous malformations, and performing preoperative assessments. Further, MRA and other 3D angiographic images provide useful assistance for surgical procedures. The display of catheter angiograms and/or MRA image data have been found to be important aids during aneurysm surgery. The usefulness of the display of 3D angiographic image data during surgery can be enhanced by the display of the angiographic images in conjunction with 3D images of other types of anatomy such as adjacent bone structures or critical organs.

SUMMARY OF THE INVENTION

According to the present invention, a method and system are disclosed for enhancing and segmenting a multi-dimensional image based upon the depth buffer (or "Z-buffer") that is generated in conjunction with a maximum intensity projection (or related point selection projection) operation through the multi-dimensional image. This enhancement and segmentation is referred to as the depth-buffer segmentation (DBS) process. The DBS process segments an MRA image volume into regions having a likelihood of vessel occupation and regions that are unlikely to contain vessels. The process reduces the total image volume to a much smaller volume so that the amount of

territory that a user must cover is greatly reduced. In addition, projection images of the vascular information found within the data become much more refined and visible when the background regions have been removed.

The DBS process merges the global properties of the MIP process with the local properties of continuity to achieve a high specificity in the segmentation of vessel voxels from background voxels while maintaining a high sensitivity. The segmentation provides an accurate and robust view of the vessel structure and filters out most of the non-vessel regions in the image. After the vascular detail is segmented, it can then be converted back to image data for display - for example, as a densitometric summation of the MRA image data resembling that of an X-ray angiogram. In an optional step, the dynamic range of the display is reduced by hollowing out the vessel structures and displaying the vascular details as X-ray projection through hollow tubes. Further, the image may be modified by adding a degree of shading so that the 3D vessel structure is apparent in a manner not visible in X-ray images. Such image shading was not possible in the MIP process.

In one embodiment, the method generates a reduced dimensionality image data set from a multi-dimensional image by formulating a set of projection paths through image points selected from the multi-dimensional image, selecting an image point along each projection path, analyzing each image point to determine spacial similarities with at least one other point adjacent to the selected image point in a given dimension, and grouping the image point with the adjacent point or spacial similarities between the points is found thereby defining the data set. The method, within the analyzing step, the step of determining similarity of brightness between the image point and the adjacent point. Further, the analyzing step also determines similarity of smoothness between the image point and the adjacent point. In one example, the smoothness is determined by using a least squares fit of adjacent image points. In yet an alternative embodiment, the method further includes selecting another image point along the projection path and performing the analyzing and grouping steps on the newly selected image point. Further still, the method may also convert the grouped and ungrouped image points into a multi-dimensional image and then perform region growing within the converted multi-dimensional image or perform hollowing-out of the multi-dimensional image for image enhancement. Another image enhancement steps include removing all pixels that are surrounded on each side by an adjacent pixel prior to displaying the image of the merged and unmerged image points.

The system further defines an image processing apparatus that comprises means for defining a set of projection paths through a multi-dimensional image, means for

selecting at least one point, along each projection path, based upon a specified criterion, means for formulating an array of projection values corresponding to the positions of selected points along their respective projection path, and means for grouping a selected number of projection values based upon their proximity to other projection values. The apparatus essentially is a programmable computer system that loads a particular software program capable of implementing the steps of the method claims within a computer architecture environment for manipulating the data and processing it for imaging, whether the imaging is in a printed image or a displayed image, such as on a computer monitor. Further still, the method may be implemented in a computer program product for sale or distribution, whether that product is in a portable medium or in a fixed medium or remote medium that is communicated via a communications source, such as the Internet or other communication means known to those skilled in the art.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing will become more fully apparent from the following description and appended claims, taken in conjunction with the accompanying drawings. Understanding that these drawings depict only typical embodiments of the invention and are, therefore, not to be considered limiting of its scope, the invention will be described and explained with additional specificity and detail through the use of the accompanying drawings in which:

Figure 1 illustrates a block diagram of the imaging system utilizing depth-buffer (or Z-buffer) segmentation in accordance with the present invention;

Figure 2 illustrates a flow diagram of the method steps implemented by the imaging apparatus of Figure 1 in rendering DBS images in accordance with the present invention;

Figure 3 illustrates a standard axial MIP image of a patient with a large ophthalmic artery aneurysm;

Figure 4 illustrates a depth-buffer or Z-buffer array corresponding to Figure 3 in which brightness is proportional to the "Z" location of each point selected for the MIP along each projection line;

Figure 5 depicts a plot of the intensity values of the data from the projection lines for the 30 points indicated by the short line that crosses the middle cerebral artery as shown in Figure 4. The z-locations of the maximum intensity values projected by the MIP algorithm are indicated by the vertical marks.

Figures 6 through 8 illustrate an expanded view of the small region of the Z-buffer array of Figure 4 where Figure 6 illustrates example line segments used for the

least squares fit roughness calculation, Figure 7 illustrates image brightness inversely proportional to the roughness values in accordance with the present invention, and Figure 8 illustrates the same region with brightness set proportional to group size after grouping low roughness pixels that have similar depth values - i.e. have connectivity in the Z-buffer;

Figures 9 through 11 illustrate a series of images where each image represents where Figure 9 is a brightness inversely proportional to the roughness value in accordance with the present invention, Figure 10 is a brightness based upon number of points connected in the Z-buffer, where connectivity is based upon local smoothness and proximity in the depth or "Z" direction, and Figure 11 is a brightness proportional to number of points connected after connectivity has been enhanced by the 3D region growing process;

Figures 12 through 14 illustrate part of an original 3D image with the corresponding segmented image and also the segmented image overlayed on the original image.

Figure 15 illustrates the performance of the segmentation based on a vessel and non-vessel classification of the segmented image of Figures 12 through 14 as performed by an independent observer;

Figures 16 through 18 illustrate stereo pair X-ray-like densitometric projections (DPs) of the DBS segmentation corresponding to the image of Figure 3, where Figure 16 is the DP of all segmented vessels, Figure 17 is the anterior circulation, and Figure 18 is a combination of DP and shaded surface display of a hollow representation of the DBS segmentation of the anterior and posterior circulations;

Figures 19 through 22 illustrate stereo pair X-ray-like DPs, based on the principles of the present invention, of the intracranial circulation of a patient with a posterior communicating artery aneurysm and a basilar tip aneurysm ;

Figures 23 through 24 illustrate stereo pair X-ray-like DPs of a contrast enhanced abdominal aorta in accordance with the present invention; and,

Figures 25 through 26 illustrate a set of CTA images including (A) axial collapse of segmented data structures and (B) shaded hollow-body reprojection in accordance with the present invention.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

It will be readily understood that the components of the present invention, as generally described and illustrated in the figures herein, could be arranged and designed in a wide variety of different configurations. Thus, the following more detailed description of the embodiments of the system and method of the present invention, as

represented in Figures 1 through 26, is not intended to limit the scope of the invention, as claimed, but is merely representative of the presently preferred embodiments of the invention. Likewise, the following description focuses on the capability of the present invention to isolate blood vessels for enhanced angiographic imaging, but this is not intended to limit the potential uses for which the invention may be of value to only those examples given.

The presently described embodiments of the invention will be best understood by reference to the drawings, wherein like parts are designated by like numerals throughout.

Figure 1 illustrates a block diagram of an imaging apparatus 10 in accordance with the present invention. Imaging apparatus 10 comprises an imaging device 12, a Z-buffer MIP processor 14, an image processor 16, a storage system 18, output device 20, and image viewing device 22. Each element is connected with at least one other element within apparatus 10 or, alternatively, each element is connected to a common bus 23 that allows communication to and from each element with any other element within apparatus 10.

Imaging device 12 typically is a magnetic resonance imaging (MRI) system or a computed tomography (CT) system or a rotational X-ray CT angiography (XRCTA) system used in generating 3D images in a non-invasive manner of a subject, such as an object or a patient, which images can be stored in computer manipulable form for subsequent processing and display. Z-Buffer MIP processor 14 and storage system 18 are typically selected as a personal computer-type system or work station. One such system includes a personal computer based on the Advanced Micro Devices (AMD) Athlon 650 megahertz CPU with a storage system comprising 128 megabytes of RAM and a 20 gigabyte long-term storage hard drive. Alternatively, the computer system can be selected from other known computer systems as previously mentioned, such as for example, a work station like that provided by Sun Computers, such as their UltraSpark Platform. The computer system further incorporates the image processor 16. One image processor suitable for use is provided by Mitsubishi and is known as the VP 5003D graphic accelerator. The personal computer system operates in a Windows NT operating system environment. Other operating systems include Windows 98 and Windows 2000, which are both provided by Microsoft of Redmond, Washington. Further, the invention can be implemented on an Apple compatible system running under OS 9 and configured in a comparable manner to the personal computer mentioned above.

Output device 20 can include such items as a printer system or removable storage device. The printing systems typically utilized as output devices offer a high quality output such as those found in digital photography printers. Other printers, including low

resolution laser printers, would also be acceptable in some situations. Typically, however, the use of better resolution in printing is desirable. Image viewing device 22 typically is a video monitor. The monitor typically is a high resolution monitor given the large amount of image detail that is of interest. The depth-buffer segmentation process makes it feasible to include a graphical user interface to allow a user to select different viewing options, different angles of view, rotational viewing options, and other animation-type viewing options, which enhance and optimize the viewing needs of the user.

The operation of apparatus 10, as well as the process for converting raw image data information into a useful depth-buffer segmentation (DBS) image, is shown in the flow diagram of Figure 2 and is presented in greater detail below in accordance with the present invention. In order to begin processing an image, an image must be generated or taken of the subject matter to be examined. The image or images can come from various imaging modalities. These modalities can be selected from magnetic resonance imaging systems or other 3D imaging systems. Other imaging modalities include computed tomography (CT), computed tomography angiography (CTA), and X-ray CT angiography (XRCTA) as well as other types of 3D imaging systems known to those skilled in the art. Further, it is the image data itself that is useful and processed as will be shown below.

In experiments made to evaluate the process of the present invention, image data acquisition was performed as part of an aneurysm imaging protocol. The imaging was performed on a 1.5 Tesla (T) General Electric model Signa MRI scanner with actively shielded gradients. The gradient system operates with a maximum strength of 23 milli-Tesla/meter (mT/m) and a slew rate of 77 milli-Tesla/meter/millisecond (mT/m/ms) on all three axes for the MRA sequence. An optimized cylindrical birdcage transmit/receive coil with an RF mirror endcap is used. Generally, the image is acquired in any desired technique, one of which is illustrated in the acquisition of step 212, which uses a three-dimensional time-of-flight (TOF) sequence. The 3D TOF sequence incorporates imaging techniques such as abbreviated magnetization transfer, flow compensation in the frequency and slice-encode directions, and RF spoiling, which are understood by those skilled in the art. For this image acquisition process, the imaging parameters used and that are understood by those skilled in the art were: repetition time (T_R) = 48 msec, echo time (T_E) = 5.3 msec, readout bandwidth (RBW) = ± 16 kHz, "in-plane" matrix = 512 x 192 image elements, field of view (FOV) = 220 x 165 mm².

The next step, step 214, although optional for the present invention, applies zero filled interpolation in all 3 image directions. After the optional interpolation, step 216 applies MIP processing to the 3D image data. MIP processing involves generating a 2D

image from the 3D image, where the image value selected for each point in the 2D image is the maximum (or minimum) image value found along a corresponding line through the 3D image. The MIP projection lines may all be parallel, as in a parallel ray MIP image, or the lines may be non-parallel and for example might diverge from a single source point as in a divergent ray MIP image or in curvilinear space as well.

In step 218 an array is generated from the original 3D image data by determining the depth or Z-positions of the points included in the MIP image. In this Z-buffer array, the value of each element is related to the distance of the corresponding point in the MIP image from the 2D image plane (i.e. the location of the maximum (or minimum) intensity value along each projection line). Figure 3 illustrates a standard axial MIP image of a patient having an ophthalmic artery aneurysm. The image was acquired in a 512 x 256 x 64 image format and then interpolated to 1024 x 1024 x 128, which is shown in step 214. The image is generally considered to have high quality, but the artifacts inherent in the MIP algorithm, such as vessels obscured by other vessels, are visible. Figure 4 displays the depth-buffer (or Z-buffer) array corresponding to the axial MIP image of Figure 3. As noted, the Z-buffer array values, displayed here as levels of brightness, are proportional to the depth or "Z" positions of the points that appear in the MIP image of Figure 3.

The generation of the MIP with the Z-buffer may actually be formed in any direction through the original 3D MRA image data. A convenient direction that is chosen in the samples previously mentioned and that is used in the current embodiment is to perform the MIP in the original slice selection direction. Typically, the path will be along a defined line taken for evaluation, whether it be a straight line, a divergent line, or a curvilinear line, as determined by the operator at the time the evaluation is performed.

Figure 5 illustrates a plot of signal intensities along the projection lines in the original 3D image data for 30 points taken from Figure 3. The vertical marks on the 30 plots of Figure 5 show the positions and values of the points that projected into the MIP image in Figure 3. Each of these lines corresponds to a point in the vertical bar that crosses the right middle cerebral artery shown in the display of the Z-buffer array of Figure 4.

Two observations are made looking at these illustrations. The first is that the vessels exhibit very high continuity in position in the "Z" location. This continuity is used in a primitive vessel detection algorithm that generates a value based on the smoothness in at least one direction around a point. For example, the intensities in the image of Figure 7 are inversely related to the minimum χ^2 value obtained from the first order fit of 5 points in the four principal directions around each point of Figure 6, which

is a magnified view of the region indicated with a small rectangle in Figure 4. The four principal directions are defined as 0, 45, 90 and 135 degrees from horizontal in the 2D image plane. For those points where the χ^2 value is low in at least one direction (smooth neighborhood), the image is bright. As will be shown, the vessel segments visible in the MIP of Figure 3 are all characterized by smoothness and continuity. In view of this, the process of performing depth-buffer segmentation consists in grouping image points based on this smoothness and continuity. The major vessels are characterized by large groups of points.

The second observation is that the apparent width of the vessel "continuity" region in the Z-buffer array display is noticeably wider than the apparent width of the vessels in the MIP image (Figure 4 as compared to Figure 3). This difference in width is explained by noting that the slow flow of blood near the vessel edges results in very low signals. Yet, the signals at the vessel edges can still be sufficiently strong to cause many of these edge points to project in the MIP image. Hence, the edge points are present in Figure 3 even though their brightness is scarcely distinguishable from the background. In the Z-buffer array of Figure 4, the edge points are seen to have the same depth as the brighter central points of Figure 3, confirming that they pertain to the same anatomical structure.

The apparatus and process of the present invention measures the local roughness for each element within the Z-buffer array in accordance with step 220. The process measures the roughness (or smoothness), as described below, in the Z-buffer array. In most areas of the Z-buffer array, only pixel groups from vessels exhibit smoothness in one or more directions. To measure the smoothness, the process performs a low order polynomial least squares fit to Z-buffer array values (MIP image Z-locations) in the four principal directions around each point in the Z-buffer array. The four directions are shown in the upper left hand quadrant 600 of Figure 6. Beginning with the brightest point in the MIP image, every point in the MIP image is tested for classification as vessel based upon local smoothness in the corresponding Z-buffer array. If the element is found to be locally "smooth" the process tests all eight neighbors in two dimensions for additional possible vessel elements. If the neighboring elements are also "smooth" and if they are close in "Z," they are added to the group and their neighbors are added to the list for testing. The process continues until all neighbors to the group are too "rough" or too separated in "Z" to be connected.

The process then considers the next nonclassified, brightest point in the MIP image and tests whether it is a "smooth" element. If this element is smooth, it is defined as the next group and the method repeats the process of looking for additional members

to add to this new group. The process continues until all elements in the Z-buffer array have been tested.

Figure 6 illustrates an expanded view of a small region of the Z-buffer array of Figure 4. The four small line segments, segments 610-616, show the length (5 pixels) of the segment used for the first order least squares fit. Points 610 and 614 are outside vessels and yield a high χ^2 value for the fit in any direction. Point 612 is within a vessel, but yields a high value except for the direction parallel to the vessel. Point 616 is within the vessel and yields a low value for three out of four possible directions. Figure 7 illustrates the same region as Figure 6, where the image brightness of each pixel is inversely proportional to its minimum calculated roughness value, or χ^2 value, as specified below. The χ^2 value for the fit in the j th direction ($j=1,2,3,4$) for the i th element in the Z-buffer array is:

$$\chi_{ij}^2 = \sum_k (Z_{ijk} - P_{ijk})^2$$

where Z_{ijk} is the Z-buffer value (depth-buffer value) for element number k ($k=1,2,3,4,5$) along the line having element i at its center and direction j . The P_{ijk} corresponds to a predicted value for the same element determined from a low order polynomial fit to the values along the line. The brightness in the array shown in Figure 7 is then inversely related to the minimum χ^2 value. For each point i and all corresponding lines $j=1,2,3,4$:

$$\chi_i^2 = \text{MIN}_j (\chi_{ij}^2)$$

and brightness, V_i , is

$$V_i = A/(B + \chi_i^2)$$

where the constants A and B are empirically determined. The brightness values displayed in Figure 7 tend to increase with the likelihood that the element is part of a vessel.

Other methods of measuring smoothness in the MIP Z-buffer could be used. The current method involves performing a low order least squares fit to a small number of image elements centered at a particular point. In the current embodiment, the process utilizes a first order fit along five points, and an example of applying the fit in four principal directions is shown in Figure 6. Alternatively, a different number of points, a different order fit, and a different number of directions may be used in measuring local

roughness or smoothness as desired by the system designer. Or the process could be omitted completely in some implementations.

As may be deduced from Figure 6, only points that are contained within vessels will have a very low χ^2 value. Points just outside the vessel edges generally experience erratic Z-buffer depth values at some point along each of the lines selected for the fit, resulting in high χ^2 values. Because a vessel only requires smoothness in one direction, the process saves only the minimum value of the χ^2 for each point. The minimum χ^2 image is illustrated in. Figure 9 illustrates an image where the brightness is inversely proportional to the minimum χ^2 value of the least squares fits of short line segments along the principal directions.

It is then possible to look throughout the minimum χ^2 image for regions of connected "smoothness" as performed in Step 222 of Figure 2 in order to determine regions that are most likely to be vessels. Such regions are indicated by the grouped image elements of Figures 12 through 14. Figures 12 through 14 illustrates points in the Z-buffer that are grouped together based upon their low roughness values and proximity. The brightness shown in Figures 12 through 14 is proportional to the number of points in each group.

In the implementation of step 222, the process performs a grouping operation where each data point is considered in a specific order. The use of the MIP image implies that the bright parts of the original three dimensional image data were the most important. As such, the process performs the connectivity operations by selecting the brightest image element in the MIP image. This element is tested for a low value in the corresponding minimum χ^2 array. If the minimum χ^2 is below a predefined threshold, the point is selected as a possible vessel and the neighboring points in the 2D MIP image are tested. The brightest element and all of its neighbors and their neighbors, and so forth, which satisfy the connectivity criterion, are added to the group. The process then considers the next non-classified brightest point and determines which remaining neighboring points satisfy the connectivity criterion to form another group. The process continues until all points have been tested. To be connected in this embodiment of the invention, the minimum χ^2 value must be below a given threshold and the Z-position must be within a small distance of the currently considered point. For example, in this illustration, the threshold value for χ^2 equaled 1.0 and a step of +/- 2 in Z was allowed. Other values may be selected by the designer according to the needs of the designer, but this step size recognizes that larger vessels occasionally project from different regions within the vessel, and the larger value improves the character of the connectedness. Figures 16 through 18 illustrates an image of the points that have been grouped based upon the

proximity in "Z" and minimum roughness. The intensity of the display is proportional to the number of points in each group. It is shown that some vessels, although obviously "connected" in real life, are not connected by this implementation of the process (e.g. the middle cerebral artery is not connected to the trifurcation area). These disconnects happen because only one point in a thick vessel is projected by the MIP algorithm, and the thickness of the vessel allows larger jumps in "Z" than are accepted by the connectivity criteria used in this example.

Once all the contiguous groups of minimum roughness are determined in the MIP Z-buffer array, there are still many vessels that are crossed by other vessels and remain broken. Further, only one point per projection line is included in the vessel group. It is therefore useful to map each group of vessel points back to their original three dimensional image positions where a region growing algorithm is utilized for each point in each group to add additional points from the three dimensional image data to each vessel group as shown in step 224. In step 224, to complete the process of connecting all vessels, the groups are mapped back to the three dimensional image space, and all points from the two dimensional groups are considered again in the same order. All neighboring points in the 3D data are tested based upon their intensity being a selected (e.g. two standard deviations) above the average background value. Points that are two standard deviations or more above the average background would have projected in the MIP image had they not been obscured by other brighter structures, such as vessels. By adding these points to the groups, the process fills out the vessels in 3D and also connects most branches that were "disconnected" by being obscured by other vessels. An image of points connected by the process in step 224 is illustrated in 11.

As indicated by step 226, extraneous groups are removed from the set of grouped image points created in step 224. For example, noise groups can be removed automatically by eliminating all groups with very small numbers of elements. In this example, all groups with less than 45 elements were considered to be noise and were removed. All the major vessels subtend more than 45 elements, and very few noise groups have more than 45 elements (voxels). Where groups with large numbers of voxels are not of interest, such as regions of fat or bone or organ tissue in angiographic imaging, they can be eliminated by a manual step, that allows the user to select the groups to be removed and cause those groups not to display.

A qualitative evaluation of the results of the segmentation process can be performed by comparing the elements segmented as belonging to vessels with those seen in the original cross-sectional images. The DBS process performs well in classifying vessel and non-vessel voxels. The misclassifications consist of the smallest vessels that

did not appear in the MIP and the centers of the carotid arteries that were dark in the original 3D data. Figures 12 through 14 show an example of points in the original 3D image that, as shown in Figure 15, were manually classified as vessel and non-vessel by an independent observer. The points segmented by the DBS process of the present invention as vessels and non-vessels are shown as white and black regions of points in Figures 12 through 14. The manually classified points appear as white points in these same figures. Figure 15 illustrates graphs of the performance of the segmentation based on the vessel and non-vessel classification of the segmented image of Figures 12 through 14 as performed by an independent observer. The graphs represents the vessel inclusion sensitivity as measured by the number of voxels in a group of a few hundred and of x1000. Line 910 represents very small vessels means only see in local projections. Line 912 represents small vessels as seen in the MIP images. Line 914 represents the medium size secondary bifurcations, M2, A2. Line 916 represents large vessels, such as internal carotid and middle cerebral arteries.

Once all of the data elements have been classified by the DBS algorithm as groups of structures such as vessels, any of the previously mentioned variety of display techniques may be utilized, including MIPs and shaded surface renderings. By displaying the original MRA intensities of only those points classified as vessel, it is straightforward to perform densitometric summations along lines to the original data. The resulting images, as shown in Figures 16 through 18, look much like subtraction X-ray angiograms, but the dynamic range is so large that it is hard to portray the vessels at a single window/level setting on a video display. More specifically, Figure 10 illustrates a stereo pair X-ray-like densitometric projection through DBS process images from the aneurysm study of Figure 3. Figure 16 is a stereo pair of the full intracranial circulation while Figure 17 illustrates a stereo pair of vessels connected to the anterior and middle cerebral arteries. It is difficult to show the full dynamic range of intensities contained in the images of Figures 16 and 17. The dynamic range is reduced by removing all points internal to the DBS segmented structures. X-ray-like densitometric projection using the hollow DBS process in accordance with the present invention is shown in Figure 18. In Figure 18 some surface shading is also added to the X-ray-like projection image. In Figure 18, the intracranial carotid artery element 1010 is visible below the aneurysm. Thus, the process manipulates the dynamic range of information for display as shown in step 228 of Figure 2 to enhance the resolution of the vessel structures of interest during the display.

As just noted, one example of performing dynamic range reduction is to eliminate all data points within the image that have neighbors in every direction. This results in an

image where the vessels appear as hollow tubes. Typical displays of densitometric projections through the hollow vessel images are shown in Figure 18 and in Figures 19 through 26. The characterization of the image may be further modified by adding an amount of shading to each vessel surface thereby enabling the observer to determine whether the vessels are near or far, and the vessel orientation is more discernable as well. Once the final manipulation of the dynamic range is performed, the process, as shown in step 230, displays the processed image on an imaging device, such as a video monitor and/or prints the image on a printing apparatus. Optional display processes are contemplated that may yield more visual information. The present embodiment of the invention may not eliminate all noise, but the noise is reduced to the point that the useful data is easily recognized over these noise points.

Figures 19 through 22 illustrate stereo pair X-ray-like densitometric reprojections of the results of the DBS segmentation of points from the 3D image of a patient with a communicating artery (PCOM) aneurysm and a basilar tip aneurysm. Figure 19 is the cranial view of the PCOM aneurysm while Figure 20 is the caudal view. Figure 21 highlights the posterior communicating artery aneurysm 1108 while Figure 22 illustrates the highlight of a small basilar tip aneurysm, which is behind tip 1110 and is shown from two different orientation.

Figures 23 through 24 illustrates a stereoscopic X-ray-like densitometric reprojection through a renal artery study in accordance with the present invention. Figure 23A shows the anterior view while Figure 24 illustrates the posterior view.

Lastly, Figures 25 through 26 represents an example of CTA images acquired at relatively low resolution on a helical CT scanner. Segmentation is performed with the DBS process in accordance with the present invention. Figure 25 depicts the axial collapse of the segmented data structures, while Figure 26 illustrates shaded hollow-body reprojections of the aortic aneurysm.

The DBS process as described and presented in the present invention results in an image segmentation process that is readily applicable to magnetic resonance angiography (MRA), computed tomography angiography (CTA), rotational X-ray angiography (XRCTA), and other medical and non-medical applications. Since the DBS process is based upon the generic MIP algorithm, the application of the DBS process can be extended wherever the MIP algorithm is currently being used. The utility of the DBS process can be enhanced to include display options that allow the user to toggle between the DBS process and the preliminary MIP process, as well as other forms of volume rendering. The DBS process is also applicable to such fields as computer assisted screening and image interpretation based upon segmented anatomy.

The present invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is, therefore, indicated by the appended claims, rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

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